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NASA SPACE VEHICLE DESIGN CRITERIA

NASA SP-8005

SOLAR ELECTROMAGNETIC RADIATION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform design criteria for space vehicles. Accordingly, criteria are being developed in five areas of technology, outlined as follows:

Volume I — Environment
Volume II — Material Properties and Processes
Volume III — Structures
Volume IV — Stability, Guidance, and Control
Volume V — Chemical Propulsion

The individual components of this work are regarded as being sufficiently useful to justify publication separately in the form of monographs as completed. This document, Section 1 of Volume I, Part B, Chapter 1, is one such monograph. The planned general outline of Volume I is set forth on page ii.

These monographs are to be regarded as guides to design and not as design requirements, except as may be specified by NASA project managers or engineers in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, will eventually become uniform design requirements for NASA space vehicles.

Comments from addressees concerning the technical content of the monographs are solicited. Please address such comments to the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D.C. 20546.

June 1965

PLANNED OUTLINE OF
VOLUME I: ENVIRONMENT

Volume I: Environment
Part B: Extraterrestrial Environment
Chapter 1: Interplanetary

SECTION 1: SOLAR ELECTROMAGNETIC RADIATION

1.1 INTRODUCTION

Engineering design of space vehicles, of some of their systems, and of experiments and instrumentation for space applications requires an understanding of the nature and effects of solar electromagnetic radiation. Solar electromagnetic radiation is defined as the portion of the total radiation spectrum from the sun that lies between wavelengths of 1 angstrom and 100 meters. This radiation is one of the important factors in the determination of the thermal equilibrium of spacecraft. Solar electromagnetic radiation also can degrade material properties enough, in certain cases, to cause failure of the mission. Prolonged exposure to ultraviolet radiation can cause serious damage to insulation materials and optical elements. In plastics there can be a degradation of mechanical properties—in some cases embrittlement, and in others, softening; there can be discoloration with attendant changes in such optical properties as absorption, emittance, and transmittance; and there can be changes in electrical properties.

Space vehicles that are designed to operate near the earth, other planets, or the moon must take into account, in addition to direct solar electromagnetic radiation, the solar radiation reflected from the nearby body (albedo) and the radiation emitted by the body. Reflected and emitted electromagnetic radiation are covered in other monographs.

In addition to electromagnetic radiation, the space environment contains charged-particle radiation. The effects of charged-particle radiation on space-vehicle design are also discussed in other monographs.

1.2 STATE OF THE ART

Solar electromagnetic radiation covers the spectrum from wavelengths shorter than 1 angstrom (1 Å or 10^{-8} cm or $10^{-4}\mu$) to wavelengths longer than 100 meters (10^4 cm or $10^8\mu$). To date, observations of the solar electromagnetic radiation environment have been made from the ground and from aircraft, balloons, rockets, and satellites.

Most of the energy lies between 3,000 Å and 40,000 Å (0.3μ and 4.0μ). These wavelength limits define one of several spectral "windows"—in this case, the region known generally as the "optical window"—where the earth's atmosphere is transparent to radiation. This optical window includes the visible spectrum, the region between wavelengths of about 4,000 Å and 8,000 Å (0.4μ and 0.8μ) where the human eye is sensitive to radiation. It also includes some radiation in the near-ultraviolet and the near-infrared at wavelengths where measurements may be made with optical techniques.

The solar radiation in this region is determined from measurements of solar energy received at many times during the day so that the sun is at various altitudes above the horizon. The measurements are extrapolated to intensities above the earth's atmosphere by a simple mathematical relation (refs. 1 and 2).

Errors in both the measurements of the data and the extrapolation cause uncertainties in the relative values of solar radiation and in the absolute values determined by calibration against a known standard. The data given here include the latest estimates of error based on observations, and consequently the values of solar radiation do not coincide with those given in reference 2.

In the region between wavelengths of 6,500 Å and 24,000 Å (0.65μ to 2.4μ), the data of reference 3 are considered the best available. At wavelengths greater than 2.4μ, such atmospheric constituents as oxygen, water vapor, and carbon dioxide absorb so strongly in certain wavelength intervals that solar radiation cannot be observed from the earth. However, there are a number of small, partial "windows" between 2.4μ and approximately 24μ. Radiation reaching the earth through these "windows" has been studied, but the results obtained have been only qualitative.

Recently some absolute measurements have been made from a balloon at an altitude of 31 km (ref. 4). Results of this experiment indicate that the black-body temperature of the solar disk decreases to about 5,600° K at 4μ and to about 5,300° K at 5μ. In addition, an absolute measurement from the ground at 11.1μ (ref. 5) gives a temperature of about 5,000° K.

Since there are apparently no far-infrared measurements of the solar spectrum, an interpolation was made between the point at 11.1μ and the millimeter region of the spectrum, where the black-body temperature of the sun begins to increase. It reaches $6,000^{\circ}$ K in that region and increases further as the wavelength approaches 1 cm.

The atmosphere begins to be transparent to electromagnetic radiation again at about 1 mm ($10^3\mu$). Its transparency then increases with wavelength until, at wavelengths of a few centimeters, it is very transparent and remains so until absorption by the ionosphere becomes important at a wavelength of about 15 meters.

The transparency of the atmosphere to radio waves is much greater than to visible light, and it is not perceptibly affected by varying meteorological conditions. Measurements made from the earth's surface can be extrapolated to the top of the atmosphere by the method discussed earlier (refs. 1 and 2). Instrumentation errors are responsible for the greatest uncertainties in these measurements.

There is an additional factor to consider in analyzing measurements made in this radio window. The visible sun has a radiation output constant within 1%, but at the invisible short- and long-wavelength ends of the spectrum this output is quite variable. There is a slow variation in intensity with the 11-year solar cycle, shown by the curves of figure 1 labeled "Solar Maximum" and "Solar Minimum." In addition, large and rapid increases in both radio and X-ray emission occur at the same time as certain optically observed solar flares. An optical flare is a large increase in brightness in part of the sun's atmosphere, which is usually observable only in the light of certain spectral lines such as the H-alpha line of hydrogen at 6,563 Å. Some radio "bursts" (see curves labeled "Typical Outburst" and "Large Outburst" in upper right of fig. 1) have been found to exceed the radio emission from the "quiet" sun by a factor of one million.

The ionosphere begins to absorb radio waves from the sun at wavelengths of about 15 m ($1.5 \times 10^7\mu$) and absorption is complete at wavelengths of about 40 m ($4 \times 10^7\mu$). It is expected that long-wavelength radio astronomical observations from future satellites will reveal the characteristics of the solar spectrum beyond the long-wavelength cutoff.

No radiation from the sun at wavelengths below 2,900 Å (0.29μ) has been detected at ground level. Atmospheric ozone in a layer from 10 to 40 km high absorbs the solar radiation down to wavelengths of about 2,200 Å (0.22μ). Molecular oxygen, found at an altitude of about 75 km, absorbs most of the remaining radiation down to wavelengths of about 900 Å (0.09μ). At shorter wavelengths, many atmospheric constituents absorb all the radiation before it gets within 150 km of the earth's surface.

Only rockets, satellites, and certain aircraft therefore can be used to obtain data for wavelengths below 2,900 Å (0.29μ). Besides the usual technical difficulties involved in such experiments, there are important sources of error. For the far-ultraviolet and X-ray domain, there are no radiation standards with which to calibrate measuring devices, and the data can be considered accurate only in a relative sense. In addition, errors can be produced by residual atmospheric absorption in the case of rocket and aircraft measurements and by outgassing within rocket and satellite instruments. Finally, in this region of the spectrum (as in the radio region) the sun behaves like a variable star so that results obtained at different times cannot be compared, even though the same types of instruments and calibrations are used. Consequently, in preparing figure 1 from curves of references 6, 7, and 8, some adjustment was believed justified.

The solar spectrum for wavelengths below about 1,400 Å (0.14μ) consists entirely of sharp emission lines. These have been smoothed to intervals of 50 Å (0.005μ) to make the continuous curve of figure 1. From 1,400 Å (0.14μ) to the infrared, the spectrum is a continuum with superimposed Fraunhofer (absorption) lines. This portion of the curve has also been smoothed in order to eliminate the fine detail not reproducible on this scale.

Below wavelengths of 100 Å (0.01μ), figure 1 shows some data from the Ariel I (UK-1) satellite (ref. 9) and the Orbiting Solar Observatory (OSO-1). Rocket data from the U. S. Naval Research Laboratory are presented for the quiet sun at minimum and maximum (ref. 10). Some estimates based on ionospheric studies are also included (ref. 11).

There is evidence that the solar spectrum extends down to at least 0.1 Å ($10^{-5}\mu$) during times of high solar activity, although insufficient data exist at this time to be presented.

The data and observations discussed above have been gathered into a single chart of the solar spectrum (fig. 1), which shows the distribution of the sun's radiant energy falling on an area of 1 square centimeter above the filtering effects of the earth's atmosphere when the earth is at its mean distance from the sun. The total area under the curve, which represents the solar constant, is the total energy at all wavelengths received from the sun. The currently accepted value is 2.00 ± 0.04 calories/cm$^2\cdot$min, or 1,400 watts/m^2 (ref. 1).

1.3 CRITERIA

In general, in the engineering design of space vehicles, of some of their systems, and of experiments and instrumentation for space applications, the solar electromagnetic radiation spectrum presented in figure 1 should be used.

Part of the information shown in figure 1 is repeated in table I (from ref. 1) so that the spectral irradiance may be determined with greater accuracy for a specific portion of the radiation spectrum. Data obtained outside the wavelength limits of 1,400 Å (0.14μ) and 80,000 Å (8.0μ) are not considered sufficiently accurate to be included in the table.

Because the orbit of the earth around the sun is slightly elliptical, the distance of the earth from the sun—and therefore the value of the solar constant—changes throughout the year. Use of the solar constant at mean distance as cited above results in a maximum error of ±3.5 percent.

Values of solar constant at other points in space can be determined from table II, which gives values of the solar constant for distances from the sun between 0.5 A.U. and 1.75 A.U. The A.U., or astronomical unit, is the mean distance between the earth and the sun.

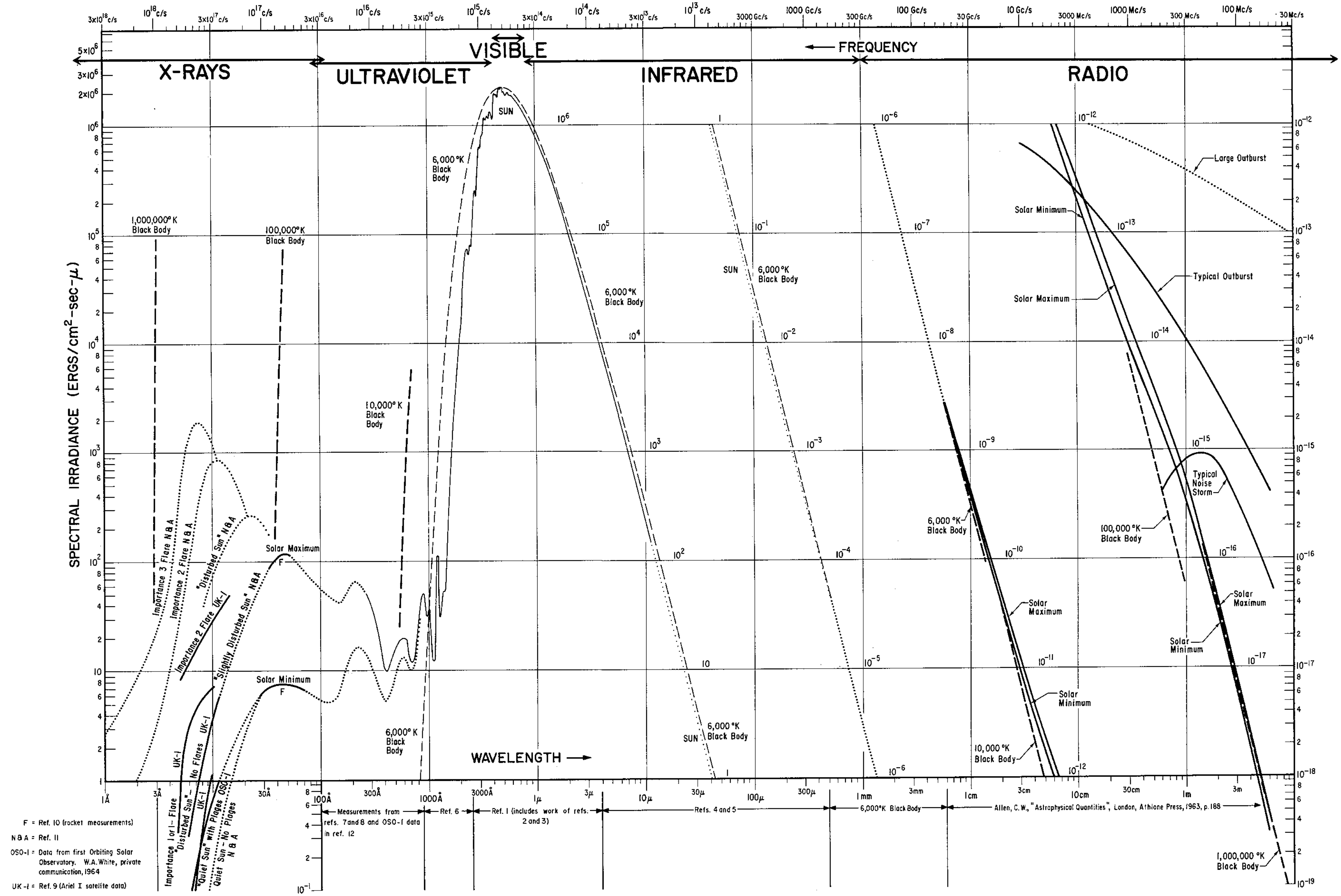

Figure 1.—The solar electromagnetic radiation spectrum. Solid lines represent measurements; dotted lines, estimates.

Table I

SOLAR SPECTRAL IRRADIANCE DATA*

λ, μ	H_λ, $w/cm^2/\mu$	P_λ, %	λ, μ	H_λ, $w/cm^2/\mu$	P_λ, %	λ, μ	H_λ, $w/cm^2/\mu$	P_λ, %
0.14	2×10^{-6}	9×10^{-4}	0.42	0.192	11.7	0.74	0.130	52.7
.15	7×10^{-6}	9×10^{-4}	.425	.189	12.4	.75	.127	53.7
.16	1.8×10^{-6}	1.0×10^{-3}	.43	.178	13.0	.80	.1127	57.9
.17	4.1×10^{-5}	1.2×10^{-3}	.435	.182	13.7	.85	.1003	61.7
.18	9.1×10^{-5}	1.7×10^{-3}	.44	.203	14.4	.90	.0895	65.1
.19	1.7×10^{-4}	2.5×10^{-3}	.445	.215	15.1	.95	.0803	68.1
.20	3×10^{-4}	3.4×10^{-3}	.45	.220	15.9	1.0	.0725	70.9
.205	5×10^{-4}	5×10^{-3}	.455	.219	16.7	1.1	.0606	75.7
.21	1.0×10^{-3}	8×10^{-3}	.46	.216	17.5	1.2	.0501	79.6
.215	1.8×10^{-3}	1.1×10^{-2}	.465	.215	18.2	1.3	.0406	82.9
.22	0.0030	0.02	.47	.217	19.0	1.4	.0328	85.5
.225	.0042	.03	.475	.220	19.8	1.5	.0267	87.6
.23	.0052	.05	.48	.216	20.6	1.6	.0220	89.4
.235	.0054	.07	.485	.203	21.3	1.7	.0182	90.83
.24	.0058	.09	.49	.199	22.0	1.8	.0152	92.03
.245	.0064	.11	.495	.204	22.8	1.9	.01274	93.02
.25	.0064	.13	.50	.198	23.5	2.0	.01079	93.87
.255	.010	.16	.505	.197	24.2	2.1	.00917	94.58
.26	.013	.20	.51	.196	24.9	2.2	.00785	95.20
.265	.020	.27	.515	.189	25.6	2.3	.00676	95.71
.27	.025	.34	.52	.187	26.3	2.4	.00585	96.18
.275	.022	.43	.525	.192	26.9	2.5	.00509	96.57
.28	.024	.51	.53	.195	27.6	2.6	.00445	96.90
.285	.034	.62	.535	.197	28.3	2.7	.00390	97.21
.29	.052	.77	.54	.198	29.0	2.8	.00343	97.47
.295	.063	.98	.545	.198	29.8	2.9	.00303	97.72
.30	.061	1.23	.55	.195	30.5	3.0	.00268	97.90
.305	.067	1.43	.555	.192	31.2	3.1	.00230	98.08
.31	.076	1.69	.56	.190	31.8	3.2	.00214	98.24
.315	.082	1.97	.565	.189	32.5	3.3	.00191	98.39
.32	.085	2.26	.57	.187	33.2	3.4	.00171	98.52
.325	.102	2.60	.575	.187	33.9	3.5	.00153	98.63
.33	.115	3.02	.58	.187	34.5	3.6	.00139	98.74
.335	.111	3.40	.585	.185	35.2	3.7	.00125	98.83
.34	.111	3.80	.59	.184	35.9	3.8	.00114	98.91
.345	.117	4.21	.595	.183	36.5	3.9	.00103	98.99
.35	.118	4.63	.60	.181	37.2	4.0	.00095	99.05
.355	.116	5.04	.61	.177	38.4	4.1	.00087	99.13
.36	.116	5.47	.62	.174	39.7	4.2	.00080	99.18
.365	.129	5.89	.63	.170	40.9	4.3	.00073	99.23
.37	.133	6.36	.64	.166	42.1	4.4	.00067	99.29
.375	.132	6.84	.65	.162	43.3	4.5	.00061	99.33
.38	.123	7.29	.66	.159	44.5	4.6	.00056	99.38
.385	.115	7.72	.67	.155	45.6	4.7	.00051	99.41
.39	.112	8.13	.68	.151	46.7	4.8	.00048	99.45
.395	.120	8.54	.69	.148	47.8	4.9	.00044	99.48
.40	.154	9.03	.70	.144	48.8	5.0	.00042	99.51
.405	.188	9.65	.71	.141	49.8	6.0	.00021	99.74
.41	.194	10.3	.72	.137	50.8	7.0	.00012	99.86
.415	.192	11.0	.73	.134	51.8	8.0	.00006	99.93

*λ = wavelength
H_λ = mean zero air mass spectral irradiance
P_λ = percentage of the solar constant associated with wavelengths shorter than the tabulated λ
1 watt = 10^7 ergs/sec

Table II

VARIATION OF SOLAR CONSTANT WITH SOLAR DISTANCE

$$\left[\text{Solar constant} = \frac{1,400 \text{ watts/m}^2}{R^2}\right.$$

where R is distance from the sun in A.U.]

Solar distance, A.U.	Solar constant, watts/m^2
0.5	5,600
.6	3,889
.7	2,857
.8	2,187
.9	1,728
1.0	1,400
1.1	1,157
1.2	972
1.3	828
1.4	714
1.5	622
1.6	547
1.7	484
1.75	457

REFERENCES

1. Johnson, F. S.: The Solar Constant. J. Meteorol., vol. 11, no. 6, Dec. 1954, pp. 431-439.

2. Dunkelman, L., and Scolnik, R.: Solar Spectral Irradiance and Vertical Atmospheric Attenuation in the Visible and Ultraviolet. J. Opt. Soc. Am., vol. 49, no. 4, Apr. 1959, pp. 356-367.

3. Moon, P.: Proposed Standard Solar-Radiation Curves for Engineering Use. J. Franklin Inst., vol. 230, no. 5, Nov. 1940, pp. 583-617.

4. Murcray, F. H.; Murcray, D. J.; and Williams, W. J.: The Spectral Radiance of the Sun From 4μ to 5μ. Appl. Optics, vol. 3, no. 12, Dec. 1964, pp. 1373-1377.

5. Saiedy, F., and Goody, R. M.: The Solar Emission Intensity at 11μ. Roy. Astron. Soc., Monthly Notices, vol. 119, no. 3, 1959, pp. 213-222.

6. Detwiler, C. R.; Garrett, D. L.; Purcell, J. C.; and Tousey, R.: The Intensity Distribution in the Ultraviolet Solar Spectrum. Ann. Géophysique, vol. 17, no. 3, 1961, pp. 263-272.

7. Hinteregger, H. E.: Telemetering Monochromator Measurements of Extreme Ultraviolet Radiation. In William Liller (ed.), Space Astrophysics, McGraw-Hill Book Co., Inc., 1961, pp. 74-95.

8. Zirin, H.; Hall, L. A.; and Hinteregger, H. E.: Analysis of the Solar Emission Spectrum From 1300 to 250 Å as Observed in August 1961. In Wolfgang Priester (ed.), Space Research III, Proceedings of the Third International Space Science Symposium, Washington, D. C., 1962, Interscience Publishers, 1963, pp. 760-771.

9. Bowen, P. J.; Norman, K.; et al.: Measurements of the Solar Spectrum in the Wavelength Band 4 to 14 Å. Proc. Roy. Soc. (London), ser. A, vol. 281, no. 1387, Oct. 1964, pp. 538-552.

10. Friedman, H.: Solar Radiation. Astronautics, vol. 7, no. 8, Aug. 1962, pp. 14-23.

11. Nicolet, M., and Aikin, A. C.: The Formation of the D Region in the Ionosphere. J. Geophys. Res., vol. 65, no. 5, May 1960, pp. 1469-1483.

12. Bourdeau, R. E.; Chandra, S.; and Neupert, W. M.: Time Correlation of Extreme Ultraviolet Radiation and Thermospheric Temperature. J. Geophys. Res., vol. 69, no. 21, Nov. 1, 1964, pp. 4531-4535.

NASA-Langley, 1965